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An assessment of renewable energy potential for electricity generation in Pakistan

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A B S T R A C T

Renewable energy for power generation is gaining attention around the world, and for Pakistan, these resources can fulfill the present and future energy demands of the country. Though the potential of renewable energy resources has been assessed in earlier studies, their assessment did not consider the most promising technologies. Moreover, their estimation was static and the future renewable resource potential was not estimated. This study estimates the current and future potential of renewable energy sources for power generation by employing most promising technologies. The technical potential of solar energy from solar photovoltaic and parabolic trough thermal technologies for power generation is estimated to be 149 GW in 2010 and 169 GW in 2050. The suitable area for wind energy generation is available for the capacity installation of 13 GW. The potential from biomass energy sources is 5 GW in 2010 and could be 15 GW in 2050. Small hydro installed capacity under current circumstances can reach 3 GW installed capacity. The current national plans are resulting in exploitation of wind and small hydro plants, but a large technical potential of solar and biomass technologies also exists. The study results clearly demonstrate that renewable energy sources can supplement the energy needs of Pakistan and can provide a sustainable energy base.

Contents

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1. Introduction

The electricity sector of Pakistan consumed 15 million tons of oil equivalent in 2008 that amounted to 28% of fossil fuels supplied to the country. Due to limited domestic oil reserves and to fulfill its energy requirement, 71% of the country's oil needs were imported in 2008 [1]. The increased use of oil in power generation sector not only increased the financial burden on the economy, but also increased CO_2 emission from power generation sector. Moreover, high oil prices curtailed the quantity of oil purchased, and therefore electricity could not be supplied as per demand of the economy, which led to demand-supply gap of electricity. Thus, total supply of electricity changed from surplus of 1230 MW at the end of financial year 2005 to a deficit of 5885 MW at the end of financial year 2010 [2]. Inability of electricity supply to match increasing demand is mainly attributed to lower utilization of existing installed generation capacity which is mainly due to increasing oil prices in international markets [2]. The average annual growth in electricity demand during 2005–2010 was 8%, and is expected to continue till 2035 [3]. If the growth continues at the same pace, the total demand will be 474 GW in 2050. The power generation plan till 2030 indicates that electricity supply will be growing at an average annual growth rate of 11% till 2030, and 65% of increase in installed generation capacity will be thermal based electricity generation [4]. Increasing fossil based generation under such circumstances will not only increase emissions but could also increase electricity prices due to the increasing prices of fossil fuels, and could make the power sector vulnerable to international fossil fuels price fluctuations. The share of renewable energy in power sector in Pakistan was less than 1% till 2010 [5]. It is, therefore, imperative that Pakistan exploits domestically available alternative energy sources for power generation. However, in order to tap renewable energy resources in Pakistan, details on the potential of these energy sources considering commercially available and most promising technologies need to be evaluated and quantified.

The renewable energy resource potential of Pakistan has been assessed by a number of researchers [6–11]. However, their estimations were limited to theoretical potential of energy extraction from the renewable sources and their possible utilization for different energy applications like cooking, heating, drying, etc. These studies also focused more on solar energy potential and not much on other renewable resources. Very few studies estimated the technical potential of electricity generation from solar and wind energy. Sheikh, [9], for example, estimated the technical potential of solar PV generation capacity for 100 square kilometers which is 0.01% of total land area of the country. Gondal and Sahir [11] assumed 0.45% of urban areas for PV installations to estimate the installed capacity of electricity generation through solar PV. However, these studies did not describe the technology considered and did not provide the details on the estimation of suitable area for the deployment of the technology. Moreover, future geographical and technical potential was also not estimated. This study aims to fill the gap of renewable energy resource availability of Pakistan by estimating the current and future geographical and technical potential of mature, commercially available renewable energy technologies for electricity generation. This study assesses the existing and future potential of major renewable energy sources, namely, solar, wind, small hydro and biomass in Pakistan, by considering the most promising energy technologies. More specifically, the study endeavors to find how much renewable energy resource is available for power generation in Pakistan? And how much electricity can be generated using currently available renewable energy technologies?

The organization of the paper is as follows: Section 2 provides a brief description of the types of potentials. Sections 3 presents the assumptions and the methodology adopted for the estimation of resource potential, respectively. Section 4 is devoted to the estimation of different potentials under geographical and technological constraints for the various renewable energy resources. Section 5 discusses the technical potential of selected renewable energy sources, the renewable energy promotion plan and its (practical) implementation. Section 6 concludes the study.

2. Renewable energy resource potential definitions

The potential of renewable energy (RE) is the energy which can be provided by the specific source annually. However, this potential depends upon geographical, technical and economic limitations [12]. RE potential has been defined in many ways (Table 1). Boyle [12] has suggested four potentials, namely, total, technical, practical and economic potential. Vries et al. [13] used geographical, technical and economic potential to explain the concept of potential. These definitions are based on World Energy Council Report 1994 and Hoogwijk [36]. Painuly [14] differentiated the techno-economic potential and economic potential on the basis of market distortions. Brief definitions of these different potentials are as follows:

- Theoretical potential[1] : The highest level of (resource) potential is the theoretical potential. This potential only takes into account restrictions with respect to natural and climatic parameters.
- Geographical potential: The geographical potential is the theoretical potential limited by the resources at geographical locations that are suitable for installation of specific technology.
- Technical potential: This is the geographical potential which can be attained using technically feasible technologies while accounting for conversion efficiencies.
- Techno-economic potential: This is the potential which can be availed by applying technically feasible and economic viable technologies which are being universally used in competitive markets.
- Economic potential: The economic potential is the technical potential at cost levels considered competitive.

[1] Total potential and theoretical potential are two names of the same concept, and it is total availability of the energy from specific RE source [13].

- Market potential: The market potential is the total amount of renewable energy that can be implemented in the market taking into account the demand for energy, competing technologies, the costs and subsidies of renewable energy sources, and barriers.

This study follows the definitions given by Vries et al. [13] and distinguishes the potential as geographical, technical and economic potential. The paper presents the availability of renewable energy potential which can be tapped through commercially mature technologies, and is limited to estimation of technical potential.

3. Methodology and assumptions

Renewable energy sources for electricity generation can broadly be categorized as combustible and non-combustibles. Electricity generation from combustible renewables (e.g., biomass) depend upon the availability and the quality of resource for combustion, whereas noncombustible renewables (e.g., Solar and wind) are more site specific, and depends on climatic conditions.

The methodology to estimate the potential of each renewable energy source is thus different due to varied nature of the source, and due to the geographic and technological limitations of each source. However, the general methodology used for the assessment of the different renewable energy resources potential is shown in Fig. 1.

Table 1
Types of potential defined by existing studies.

Potential types	Boyle [12]	Vries et al. [13]	Painuly [14]	Hoogwijk and Graus [15]	Resch et al. [16]
Total	√				
Theoretical				√	√
Geographical		√		√	
Technical	√	√	√	√	√
Techno-economic			√		
Practical	√				
Realisable					√
Economic	√	√	√	√	
Market			√	√	

The mathematical representation for the estimation of renewable energy resource potential is as follows:

$$Gp = Ep \times Ra \tag{1}$$

where, Gp is geographical potential (GW h); Ep is energy potential of renewable energy resource (GW h/unit of energy source (km^2 or ton)) and Ra is resource availability (million tons, km^2). Non combustible energy resources (solar, wind and hydro) are site specific and tapping energy from these sources is possible only in certain areas and depending on the technology deployed. Therefore, resource availability for these is the availability of suitable area (km^2). Geographical potential of combustible resources (biomass) is estimated on the basis of residue availability (million tons).

The technical potential is estimated by applying the capacity factor and the electrical conversion efficiency of renewable energy technology, as:

$$Tp = Gp \times Cf \times Eff \tag{2}$$

where, Tp is technical potential (GW, GW h); Cf is the capacity factor of technology (fraction); and Eff is efficiency of the technology (%). Availability factor refers to number of days/hours per year the technology can be used for electricity generation. The value is lowest for solar technologies (0.33) due to their dependency on sunshine.

Though, the assumptions and methodologies for the assessment of each renewable resource potential differ (and are elaborated in relevant sections), the general assumptions considered for the potential estimation in this study are listed below:

- Though renewable energy carriers are used for heating, cooking, cooling, drying and electricity generation, the present study considers the renewable resource use only for grid connected electricity generation.
- Centralized (CNT) and decentralized (DCNT) systems are considered for solar PV technology, while for other technologies only centralized electricity systems are considered.
- Off shore technologies are not considered due to data limitations regarding their potential.
- Area under forests, restricted areas and water bodies are excluded in the assessment of resource potential.

The specific methodology for each renewable resource is described in the following section.

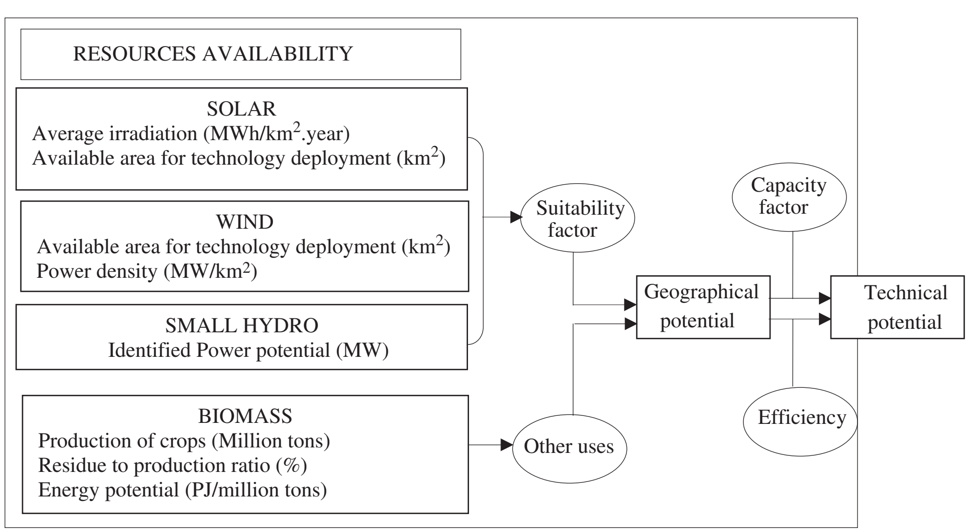

Fig. 1. Flow chart representation for the estimation of potential estimation of renewable energy sources potential.

4. Estimation of the renewable energy sources potential

4.1. Solar energy

4.1.1. Resource description and availability

Solar energy is the energy that is available in the sun light or in the heat generated by sunlight [17]. Sun light reaches the earth's surface in the form of solar radiation and the average intensity of solar radiation outside the atmosphere is 1367 W/m^2. Due to atmospheric attenuation, the intensity reduces and the resulting peak intensity at sea level is around 1 kW/m^2. The amount of irradiation varies regionally with the changing seasons, and hourly due to daily variation in sun's elevation [18].

Pakistan is situated between latitudes 24° and 37° North, and longitudes 62° and 75° East with an area of 796,096 km^2. The solar radiation incident is in the range of 5–7 kW h/m^2/day over 95% of the total area with persistence factor of over 85% [7,19,20]. The mean global irradiation on a horizontal surface in Pakistan is about 200–250 W/m^2 with 8 to 10 sunshine hours per day [7].

4.1.2. Overview of technologies

Solar PV and solar thermal are the two common generic technologies used for electricity generation [21]. The present study considers these two technologies for the estimation of the potential of solar based electricity generation in Pakistan.

4.1.2.1. Solar PV. Solar PV is a most promising and well established technology to convert sunlight to electricity [18,22–26]. PV cells are usually linked in series/parallel combinations within weather proof modules to form larger power arrays [24,25]. PV technologies can be installed for single user (off grid) or for multiple users (grid connected).

Commercial PV technologies can be divided into three categories i.e., first generation (Crystalline silicon (c-Si)), second generation (Thin Film (Cd–Te)) and third generation (Concentrator Photovoltaic (CPV)) technologies. Thin film technologies are the cheapest, but have low efficiency, whereas CPV technologies are most efficient but are very costly, and are not yet commercially mature [26]. Crystalline Silicon (c-Si) technologies systems are predominantly used all over the world due to mid range costs, reasonable efficiencies and lower space requirements [26–28]. The overall share of c-Si in 2009 was estimated to be in the range of 85–90% of the global annual PV market [25].

4.1.2.2. Solar thermal. Solar Thermal or Concentrating Solar Power (CSP) Systems are also used for electricity generation in addition to Solar PV systems. In CSP systems, concentrated solar radiation is converted to thermal energy first before it is converted to electrical energy. A CSP plant is comprised of solar collectors, receivers, and a power block. The solar collectors concentrate sun light to raise the temperature of transfer fluid in the receiver. The heated fluid produces steam which is then used to generate electricity through a conventional turbine generation system [29,30]. These systems can be categorized as point focus concentrators and line focus concentrators. Point focusing systems have two types of power plants—solar tower and solar dish systems. Line focusing systems include parabolic trough and linear Fresnel plants [30–32]. CSP plants can be equipped with heat storage system to generate electricity even in cloudy sky or at night time [33]. Table A-1 (Appendix-A) presents the comparison of main types of CSP technologies in terms of their technical characteristics. These technologies significantly differ from one another not only on technical features, but also in relation to reliability, maturity and operational experience [33].

Table 2
Status of CSP projects in the world market till 2011 (capacity in MW) [35].

Technology	Operational	Under construction	Planning phase	Total
Parabolic trough	1211	1210	2780	5201
Power tower	36	387	1505	1928
Dish engine	2	0	750	752
Linear fresnel	6	30	0	36
Total	1255	1627	5035	7917

The Parabolic Trough systems are the most popular CSP technologies. These are commercially mature and cost effective among all CSP technologies and have attracted considerable interest from energy utilities in Europe and USA [30,32,34]. The share of parabolic trough technology in operation is 97%, whereas under construction and planned capacities, its share is 74% and 56%, respectively [35]. Table 2 gives the global status of CSP power plants.

4.1.3. Assumptions

The (specific) assumptions used to estimate the electricity generation potential using solar PV in Pakistan are:

- For DCNT (roof top solar PV) applications, 0.1% of urban rooftop area is available [36]. We assume 50% of this area for solar PV panels, and the remaining area can be used for solar water heaters [37,38].
- The future geographical potential of roof top solar PV applications is estimated on the basis of growth in urban area, which is assumed to be the same as the growth in urban population. The average annual growth rate of urban population is 2.9% during 2010–2050 [39]. In case of CNT applications, the suitable area is kept constant for the study period, due to land use competitions.
- For PV based (CNT and DCNT) applications, crystalline silicon technology is selected due to its higher efficiency and lower space requirement for grid connected applications [26,40].
- The area required to install 1 kW module is assumed to be 7 m^2 [26].
- The efficiency of commercially available crystalline silicon modules increased from few percent in 1970s to 19% in 2010 [26,40], while the average efficiency of module is 15% [40,41]. In this study, we assume efficiency of PV systems (net of losses) as 14% for both CNT and DCNT applications ([9].
- The long term solar to electric efficiency of solar PV based applications is assumed to be 25% in 2050 [26].

For solar thermal based electricity generation, the assumptions used are:

- Only parabolic trough technology has been considered.
- The area required for parabolic trough power plant is approximately 25 m^2/kW [42].
- The efficiency of existing parabolic trough plants ranges from 14% to 20% [31,35,42]. We assume the solar to electricity efficiency (net of losses) as 14%. The long term solar to electrical efficiency for solar thermal CNT system is assumed to be 25% [43].

4.1.4. Methodology

4.1.4.1. The geographical potential. The geographical potential of solar energy is the yearly irradiance integrated over geographically constrained area suitable for the considered PV system based

installations. It is estimated using the following equation:

$$GPs_{it} = 365 \times I \times Ra_{it} \quad (3)$$

where, GPs_{it} is geographical potential (TW h) of ith technology (CNT and DCNT solar PV and CNT solar thermal) in year t; I is the average solar irradiation (kW h/m^2/day); 365 are number of days in a year and Ra_{it} is the resource availability in terms of total suitable area for ith technology in year t, and t is from 2007 to 2050.

The suitable area, average daily solar irradiation, and geographical potential of electricity generation from solar based systems is given in Table 3.

The future geographical potential is based on availability of the areas for the deployment of different renewable energy technologies. The suitable area for DCNT solar PV system will increase with urban growth, whereas for CNT solar PV and solar thermal systems, the area is assumed to be the same. Therefore, their geographical potential will also remain the same. The current and future geographical potential is given in Table 4.

The estimations presented in Table 4 shows that utilization of less than 1% of total area of the country is sufficient to produce more than 2500 TW h of electricity. In 2010, geographical potential of solar electricity was 2559 TW h, which is 33 times more than total electricity consumption (77 TW h) during the same year [45]. However, all geographical potential cannot be tapped due to technological constraints. Therefore, estimation of technical potential can provide useful estimates of electricity generation from the available geographical potential.

4.1.4.2. Technical potential. The technical potential of the annual electricity generation from solar based generation has been estimated using the following equation [36]:

$$TPspv_{it} = GPspv_{it} \times n_t \quad (4)$$

$$TPst_t = GPst_t \times n_t \quad (5)$$

where, $TPspv_{it}$ is technical potential of ith solar PV technology in year t; $GPspv_{it}$ is geographical potential of ith solar PV technology in year t; η_t is conversion efficiency of the technology in year t, and Pr_t is performance ratio in year t. Similarly, $TPst_t$ is technical potential of solar thermal technology; $GPst_t$ is geographical potential of solar thermal and η_t is conversion efficiency of the technology.

The technical potential thus estimated for 2010 are 19 TW h, 220 TW h and 119 TW h for solar PV DCNT, CNT and solar thermal CNT, respectively. The total technical potential from solar based electricity generation systems is thus 358 TW h.

The future technical potential depends upon the improvements in conversion efficiency of solar energy into electricity. Innovation and research & development activities in solar technologies are not only reducing the unit cost but also increasing the efficiency of these systems [26]. Increase in efficiencies is therefore considered in the estimation of future technical potential. Based on the assumptions noted above, the long term technical potential (up to 2050) has been estimated and is given in Table 5.

The results indicate that Pakistan has significant potential of solar energy, which can be exploited to fulfill the increasing electricity demand. However, solar energy is not used to produce grid connected electricity so far in Pakistan. Only in 2011, utility scale ground mounted solar PV plant with 1 MW installed capacity has been initiated which will start operation in 2014 [46]. Considering the continuous electricity deficit, there should be more initiatives to increase solar energy utilization for electric power generation in the future.

Table 3
Geographical potential of solar based electricity generation during 2007.

Technology	**Type**	***As*$_{it}$ [44]**	***I* [7]**	***Gps*$_i$**
		Sq. km	kW h/day	TW h/year
Solar PV	Decentralized	62	5.3	121
Solar PV	Centralized	813		1573
Solar thermal	Centralized	565		852
Total				2546

Table 4
Geographical potential of solar energy based electricity generation (2007–2050).

Technology	**Geographical solar potential (TW h)**			
	2007	**2010**	**2030**	**2050**
Solar PV (DCNT)	121	134	258	406
Solar PV (CNT)	1573	1573	1573	1573
Solar thermal (CNT)	852	852	852	852
Total	2546	2559	2684	2831

Table 5
Technical potential of solar based electricity generation during 2010–2050.

Technology	Type of technology	**Technical potential (GW)**			**Technical potential (TW h)**		
		2010	2030	2050	2010	2030	2050
Solar PV	Decentralized (DCNT)	10	19	30	19	65	101
	Centralized (CNT)	116	116	116	220	393	393
Solar thermal	Centralized (CNT)	23	23	23	119	213	213
Total		149	158	169	358	671	708

4.2. Biomass

4.2.1. Resource description and availability

Biomass comprises all kind of organic matters produced as a result of photosynthesis reaction. It can be grouped into four catagories [47], namely:

- wood and forest residues;
- agricultural residues (from crops, food processing and animals);
- dedicated energy crops; and
- municipal solid waste (MSW).

Wood and forest residues are produced from farmlands and forest areas. Agriculture residues are comprised of residues of crops and animal waste. Crop residues can further be subcategorized into field residues and process residues [48]. Field residues are the left over part of crop in the fields. These are commonly used for cooking and heating. Process residues are obtained after processing the crops. Common examples of process residues are

bagasse molasses and rice husk. Bagasse is left over part of sugar cane processing, whereas molasses is the by-product of sugar cane and sugar beet, which is obtained during juice purification. Rice husk is the left over of rice milling and is normally used for heating, animal feed and poultry bedding. Animal waste is the waste produced by different animals, whereas MSW is the waste produced by households and commercial establishments in the cities/municipalities.

Pakistan, being an agriculture country, is rich in biomass energy sources. The main sources of biomass energy in Pakistan are crop residues and waste (animal waste and MSW). Crop residues (both field and process residues) constitute a significant part of biomass energy in the country. Residue production from major crops (wheat, rice, cotton, sugarcane, maize and gram) in 2000 was 62 million tons and is increasing at an annual average growth rate of 2%. However, this is normally used for animal fodder, cooking and heating. Animal waste is the second largest biomass energy source. There were approximately 62 million animals in 2005, growing at an average rate of 8% [49]. The average dropping of medium size animal is estimated to be 10 kg [9]. This results in the production of 62 million kg of dung per day. This dung is either disposed off in the fields or used for cooking and heating in the residential sector. MSW is the third major potential source of biomass energy in Pakistan. The average per capita waste generation in Pakistan is 0.5 kg/day and is increasing with expansion in urban population and income levels [50]. In 2005, the total MSW generated in urban areas of Pakistan was 9.8 million tons, of which 5.3 million tons was collected at an average collection rate of 57% [51]. Of the collected waste, almost 55% is organic waste, which can be used for energy generation. Utilization of these energy sources for electricity generation can help Pakistan to address its electricity crisis.

4.2.2. Overview of technologies

Conversion of biomass into useful energy depends on a number of factors, namely, type and quantity of biomass feedstock, desired form of energy, environmental standards, economic conditions and project specific factors. Under these conditions, conversion of biomass into energy is undertaken by two main process technologies—thermo chemical and bio chemical conversion. Under thermo chemical conversion, four processes are available: combustion, pyrolysis, gasification and liquefaction. Combustion and gasification processes are used for electricity generation [52–56]. Under bio chemical process, two processes are used for energy generation: Fermentation and Anaerobic digestion. Anaerobic digestion is also used for electricity generation

Under direct combustion, biomass is oxidized with excess air to produce hot flue gases at the temperature of around 800–1000 °C which is used to produce steam. The steam so obtained is used to generate electricity in a condensing steam cycle. Direct combustion is the most popular process of converting biomass into heat and power [57,58].

In the gasification process, biomass is converted into combustible gas by partially oxidizing it at high temperature ranging from 800 to 900 °C. The produced gas is used to generate electricity in a gas turbine or diesel generator [59–61].

Anaerobic digestion is used to convert organic material into biogas from high moisture content organic wastes like manure (animal and human) and crop residues. The average retention time for animal waste is 20–40 days and for organic waste it is 60–90 days [62]. The resultant biogas contains 55 to 80% methane - depending upon waste type [63].

Electricity generation from biomass depends upon the conversion technology used. The conversion technology is comprised of two components; feedstock conversion system and power generation technology. In direct combustion power generation technology, boilers are used for conversion of feed stock into steam. The generated steam is then used to produce electricity through a steam turbine. In gasification based power plants, gasifiers are used to convert feedstock into gas which is then used to drive a gas turbine to generate electricity. Table A-2 (Appendix-A) lists the available technologies which are operational or in demonstration stage. Among these technologies, steam turbine and gas turbine technologies are comparatively economical and are in common use. Gasification based technology has so far been applied on a limited scale (installed capacity is 1.4 GWe out of 40 GWe biomass based global installed capacity). It is used for combined heat and power mostly in Europe [64]. On the other hand, direct combustion based technologies (steam turbine) provides about 90% of the energy produced at global level [65].

4.2.3. Assumptions

For the purpose of estimation of electricity generation, biomass residues have been classified into three categories i.e., crop residues, animal waste and MSW.

The assumptions used for crop residue based electricity generation are:

- Only four major crops (rice, cotton, maize and gram) are considered for the estimation. Wheat and sugar cane are not considered in the estimation due to the non availability of their residue for centralized grid connected electricity generation. Wheat residue is normally used for fodder and non energy purposes [66,67] and sugar cane residue (bagasse) is used by sugar mills for self use electricity generation and (molasses) for production of alcohol or as fuel for transport sector [68,69].
- Only field residues are considered for the estimation of crop residue based electricity generation.
- The production of field residue is based on residue to production (R/P) ratio and heat value of residue which is different for each crop.
- The collection efficiency of field residues is assumed to be 35% of total residue production [52,66].
- Field residue is currently being used mainly for fulfilling the energy requirements (cooking and heating) of the residential sector. However, due to availability of commercial energy sources (LPG and natural gas), use of field residue for cooking and heating is continuously decreasing [70]. The percentage of urban and rural households consuming field residues declined from 7.6% and 37% in 1998 to 0.4% and 6%, respectively in 2006. For this analysis, it is assumed that 6% of rural households will continue using field residue for domestic use, and the remaining amount will be available for electricity generation.
- For the estimation of future potential of field residues, the average yield and area under crops in case of rice, maize and cotton for the period 2009–2025 has been projected based on available data [71]. For the remaining period, these values have been projected on the basis of 15 years (2010–2025) average annual growth rates of yield and area under crops of these respective crops. In case of gram, the area and yield has been projected on the basis of average annual growth rates of the 10 years (1998–2007). The projected area for the different crops and the average yield for the period (2005–2050) is given in Table 6.

The world average yield in 2050 for cotton, rice and maize are 2.80, 5.23 and 6.06 t/ha, respectively [72]. The projected average

Table 6
Projected area and yield of major crops of Pakistan and comparison of yield [71–73].

Crops		2005	2020	2030	2040	2050
Cotton	Area (million ha)	3103	3292	3661	4070	4525
Rice		2621	2803	2717	2634	2553
Maize		1042	1141	1215	1294	1378
Gram		129	1141	1167	1194	1222
Total		7795	8377	8760	9192	9679
Cotton	Yield (t/ha)	0.71	0.81	0.94	1.09	1.26
Rice		2.12	2.52	2.72	2.94	3.19
Maize		2.98	3.79	4.10	4.43	4.79
Gram		0.47	0.61	0.80	1.04	1.36

Table 7
Resource availability of agricultural field residues in Pakistan in 2005 [66,67,73].

Crops	Production (million tons)	R/P ratio (fraction)	Total residue	Residue collected @35% (million tons)	Energy content (PJ/million tons)	Potential (PJ)
Cotton	2.21	2.76	6.10	2.14	14.65	31.28
Rice	5.56	1.76	9.76	3.42	13.80	47.15
Maize	3.11	2.00	6.22	2.18	17.20	37.44
Gram	0.48	1.60	0.77	0.27	15.91	4.27
Total			22.85	8.00		120.15

Table 8
Resource availability of animal waste in Pakistan in 2005 [9,73,80].

No. of animals (millions)	R/P ratio (kg/animal/day)	Total residue (million tons)	Residue collected @25% (million tons)	Energy content (PJ/million tons)	Potential (PJ)
56.90	10.00	207.68	51.92	15.00	78.82

yield in Pakistan in 2050 is still lower than the maximum average yield at world level. It is even lower than current average yield of US. For example, the average yield per hectare of rice is expected to be 5.23 t which is lower than average yield of US in 2008 (5.41) [73].

- The R/P ratio, heating value and collection efficiency are assumed to be same throughout the planning period (2005–2050).
- The technology considered for electricity generation from field residue is steam turbine based direct combustion. The capacity factor and efficiency of the technology are assumed to be 65% [74] and 30% [75], respectively
- Improvements in efficiency of technology is also considered and long term efficiency is assumed to be 33% in 2050 [75].

The estimation of animal waste potential for electricity generation is based on the following assumptions:

- Only the manure from cattle and buffalo is considered. Manure from sheep and goat has not been considered due to their almost zero collection efficiency [66].
- Daily dropping of an animal is assumed to be 10 kg/day or 3.65 t/year ([9]), and its energy content is 15 MJ/t of waste.
- The collection efficiency of waste varies due to seasonal differences [76] and varies widely across countries. The collection efficiency of animal waste in China and India is around 60% [66,77,78], whereas in Bangladesh, Sri Lanka and Pakistan, it is about 50% [9,52,79]. However, studies on global biomass potential estimation indicates 25% collection efficiency for developing countries [80]. This is used in the present study.
- The dropping per animal, energy content of the waste and collection efficiency is assumed to be constant during the planning period.
- The animal waste is currently being used mainly for domestic cooking and heating. However, its use in domestic sector is declining. Percentage of urban and rural households consuming animal waste declined from 9% and 40% in 1998 to 2% and 13%, respectively, in 2006 [70]. For this analysis, it is assumed that 13% of rural and 2% of urban households will consume animal waste locally and the remaining waste will be available for electricity generation.
- The future availability of waste depends upon possible increase in number of animals. The number of animals till 2050 has been projected using the following equation:

$$An_t = An_0 \times (AVA_t/AVA_0)^{\varepsilon} \tag{6}$$

where, An_t is total number of animals in year t; An_0 is total number of animals in 2005; AVA_t corresponds to agriculture value added in year t; AVA_0 is agriculture value added in 2005 and ε is *AVA* elasticity. The agriculture value added (*AVA*) elasticity ε is estimated by log linear regression between historical data of AVA and number of animals for 27 years (1980–2007). The functional form of the model is given below:

$$Ln(An_t) = \beta_0 + \beta_1 Ln(AVA) \tag{7}$$

where, $Ln\ (An_t)$ is the total number of animals (cattle and buffalo) and (*AVA*) is agriculture value added. β_1 is AVA elasticity (ε). The value of ε is 0.7.

- The collection efficiency, per animal dropping and percentage of household using animal waste is assumed to be same till 2050.
- Animal waste is processed to generate methane which is used for electricity generation. Methane generation per ton of waste is assumed to 50 m^3 [9] with an energy content of 35 MJ/m^3 [81].
- The technology considered for electricity generation from animal waste is combustion/gas turbine, which is based on the methane generated through anaerobic process. The capacity factor and efficiency of the technology are assumed to 65% [74] and 36% [75], respectively.
- Improvement in efficiency of technology is also considered, and it is expected that electrical efficiency will increase from 36% in 2010 to 40% in 2050 [75].

The municipal solid waste (MSW) potential for electricity generation in Pakistan is estimated using the following assumptions:

- MSW generated in 10 largest cities of Pakistan is considered for the assessment.
- Waste generated in each city is estimated on the basis of population, per capita waste generation and collection rate for each city. The total waste is aggregation of waste from cities.
- Waste generation per capita per day in Pakistan ranges from 0.38 kg to 0.61 kg [82–84]. Collection rate of waste in urban areas varies from 51% to 61% [51]. The collection rate for each city has been used to estimate waste generation from that city.
- Only, organic fraction of MSW (OFMSW) is assumed to be available for electricity generation. This varies from 40% in Gujranwala to 96% in Islamabad. The average organic waste is assumed to be 56% (Table A-3 (Appendix-A)).

Table 9
Details of MSW generation in major cities of Pakistan in 2005 [39,50,82,83,86].

City	Population (millions)	R/P ratio (kg/capita/day)	Collection efficiency (%)	Residue collected (000 t)	Organic waste (000 t)	Energy potential (million m^3)
Faisalabad	2.5	0.39	65	296	136	14
Gujranwala	1.44	0.47	52	128	51	5
Hyderabad	1.39	0.56	72	374	206	21
Islamabad	0.74	0.53	91	225	216	22
Karachi	11.62	0.61	53	1378	716	72
Lahore	6.29	0.61	68	953	639	64
Multan	1.45	0.45	60	325	211	21
Peshawar	1.24	0.49	67	149	67	7
Quetta	0.73	0.38	75	100	37	4
Rawalpindi	1.77	0.58	86	320	144	14
Total	29.18			4247	2423	242

Table 10
Geographical potential (net) of biomass energy sources in Pakistan in 2005 (TW h).

	Field residue	Animal waste	MSW	Total
Total geographical potential	33	216	6	255
Used for other purpose	4	28	0	32
Available for electricity generation	29	188	6	223

Table 11
The geographical potential (net) of biomass energy during 2010–2050 (TW h).

Residue type	2010	2030	2050
Field residue	33	44	64
Animal waste	219	355	505
MSW	8	25	69
Total	260	424	638

- Future availability of MSW depends on growth in urban population and per capita waste generation. The future urban population till 2025 is based on world urbanization prospects [39]. From 2025 to 2050, the urban population is projected on the basis of average growth rate of population. The average growth rate of population is estimated by the extrapolation of growth rates of 1990–2025 for each city.
- Future growth in per capita waste generation is assumed to be 3.4% annually [85], whereas collection efficiency from different cities and OFMSW are assumed to be the same till 2050.
- OFMSW is converted into methane through anaerobic digestion. The production of methane is assumed to be 100 m^3/t of organic waste [86,87] with energy contents of 35 MJ/m^3 [81].
- Technology considered for electricity generation is gas turbine based power plant. Capacity factor and efficiency of the technology are assumed to be 65% [74] and 36% [75], respectively.
- Due to efficiency improvements, it is assumed that the efficiency of technology will increase from current 36% to 40% in 2050 [75].

4.2.4. Methodology

4.2.4.1. The geographical potential. The geographical potential of biomass (field residues, animal waste and MSW) is the amount of residue that is generated during a year. The residue (resource) availability depends upon the amount of residue base (total production of different crops/number of animal/urban population), residue per unit and collection efficiency of residue (Tables 7–9).

$$Ra_{it} = Y_{it} \times RP_i \times C_{Eff} \tag{8}$$

where, Ra_{it} is resource availability (total residue, waste) in PJ from ith generation source (crops, animal, urban population) in year t; Y_{it} is the amount of source (crop yield, number of animals, urban population) in year t; RP_i is residue production per unit of ith source, and C_{Eff} is collection efficiency.

The geographical potential of each biomass source (for 2005) is estimated by using the following equation:

$$GPb_{it} = \Sigma\left(Ra_{it} \times Ep_i\right) \tag{9}$$

where, GPb_{it} is geographical potential of ith biomass energy source in year t; Ra_{it} is the resource availability from ith source in year t, and Ep_i is energy potential of residue from ith source. i refers to major crops, number of animals and urban population. Geographical potential of field residues, animal waste and MSW for 2005 estimated using Eq. (9) was 120, 779 and 21 PJ (33, 216 and 6 TW h), respectively. However, this potential is further restricted by uses of the residue for other energy applications [88]. Therefore, the (net) geographical potential of biomass for electricity generation is total geographical potential net of other uses, and is given in Table 10:

The future geographical potential is estimated on the basis of increase in the amount of residue source and growth in residue generation rate. In case of field residue and animal waste, the rate of residue generation per unit is the same, whereas in the case of MSW, the average annual growth in residue production is 3.4%. Table 11 depicts the future geographical potential of biomass energy sources for electricity generation:

The biomass geographical potential given in Table 11 is the minimum amount of biomass energy which is available for electricity generation. This potential in 2010 is 3 times greater than total electricity consumption in Pakistan in 2010. Improvement in collection efficiency of these residues can further increase the potential of biomass for electricity generation. However technology availability and efficiency limits the actual amount of electricity which can be generated from biomass.

4.2.4.1.1. Technical potential. The technical potential of electricity generation from field residues is based on the geographical potential, efficiency and availability of the selected technology. In case of wastes (animal waste and MSW), methane is generated from residue which is used for electricity generation. Therefore, the technical potential of field residues and waste (animal waste and MSW) are estimated separately. For this purpose, Eqs. (10) and (11) are used, which are:

$$TPbw_{it} = GPbw_{it} \times M_i \times Cf \times \eta_t \tag{10}$$

$$TPbf_{it} = GPbf_{it} \times Cf \times \eta_t \tag{11}$$

where, $TPbw_{it}$ is technical potential of biomass waste residue i (animal waste and MSW) in year t; $GPbw_{it}$ is geographical potential of biomass waste residue i in year t; M_i is methane

Table 12
Technical potential of biomass energy sources during 2010–2050.

Technology	Technical potential (MW)			Technical potential (GW h)		
	2010	2030	2050	2010	2030	2050
Field residue	1744	2492	3688	9928	14,187	21,002
Animal waste	1614	2837	4140	9190	16,153	23,574
MSW	199	672	1933	1134	3826	11,004
Total	3557	6000	9761	20,251	34,166	55,581

generation rate (m^3/t) from residue i; Cf is capacity factor of technology (fraction); η_t is conversion efficiency of technology in year t. Similarly, $TPbf_{it}$ is technical potential of biomass field residue i in year t; $GPbf_{it}$ is geographical potential of ith biomass field residue in year t; Cf and η_t are capacity factor and conversion efficiency of technology, respectively in year t. Table 12 presents details of technical potential of biomass in Pakistan to 2050.

In Pakistan, there was no commercial grid connected biomass based power plant till 2011. However, recently some private firms have shown their interest in electricity generation from crop residue. SJD and Lumis power having installed capacity of 12 MW each, started construction of power plants which will be producing electricity till 2015 [46]. Besides, the government is also planning to purchase surplus electricity from sugar mills to address the electricity crises. In case of animal waste, a waste – to – energy project has been initiated in Karachi with installed capacity of 22 MW [89]. However in case of MSW, there is still no official plan to generate centralized grid connected electricity.

4.3. Wind energy

4.3.1. Resource description and availability

Wind orignates due to the difference of temperature on the surface of earth which is caused by the differential solar heating of land, water and atmosphere of the earth. Therefore, wind energy is an indirect form of solar energy [18,90]. The speed and direction of wind is affected by radiation and rotation of the earth. Moreover differential heating of the sea and land also affect the flow of air. Therefore, the areas near the coast and the areas on the edge of bodies of water have more potential of wind energy [91]. Availability of energy in wind depends upon the speed of air [92]. Wind speed increases with increase in the height above the ground.

Pakistan Meteorological Department (PMD) has conducted surveys to assess the wind energy potential throughout the country. The commercially exploitable potentail is found only in Southern Pakistan, especially in the coastal areas of Sindh and Baluchistan. The wind power potential in the coastal area is estimated by studying wind data at 20 sites. It has been estimated that suitable area in the coast belt for wind energy generation is 9700 km^2 with gross wind power potential of 43,000 MW. The power density per square kilometer is therefore 4 MW. However, land utilization constraints limits this potential upto 11,000 MW [8]. The suitable area for this potential on the basis of power density is therefore estimated to be 2481 km^2 (26% of total area). The other areas of country (Punjab, Khyber Pakhtoonkhaw, Azad Jammu and Kashmir, and northerna areas) are not suitable for exploiting wind based energy for power generation [93].

4.3.2. Overview of technologies

The power in the wind can be tapped through wind energy convertor (wind turbine) which extract energy from intercepted wind and converts this energy into mechanical form, suitable for electricity generation [18]. Wind turbines can be divided into two groups: horizontal and verticle axes turbines. Horizantal axis wind turbines are more commonly used for electricity generation and will continue holding the market in near future [90]. Major components of wind turbine are rotor (blades with hub), gearbox, generators and tower. The blades of turbine rotate due to wind, which turns the gears in a generator behind the blades and inside the turbine. The generator then converts the kinetic energy of the rotating blades into electrical energy, which is then carried by cables to an electrical grid [94]. The crucial factor in wind turbine is the rotor diameter and size of the blade. Blades with larger size can cover more swept area, and therefore capture more energy from the wind [95].

The wind turbine technology has demonstrated significant development during the last two dacades. Better exploitation of land, scale of economies, reduced investmnet costs requirements and past development funding programs pushed the industry towards development of large scale machines. Resultanatly, size of wind turbine increased from 100 kW in 1980s to 7.5 MW in 2010 (with rotor diameter of 127 m). However, after 2005, the growth in turbine size slowed down and there was more focus to increase the volume supply in 1.5 to 3 MW range due to rapid upsurge in demand at global level. Therefore, turbines in the capacity range of 1.5 to 3 MW were mainly used till 2011 [96,97].

4.3.3. Assumptions

The assumptions used to estimate the geographical and technical potential of wind energy in Pakistan are:

- Wind mills used for the purposes other than electricity generation are not considered.
- The suitable area for wind based power generation is assumed to be 2481 km^2 [93].
- The reference wind turbine used for technical potential estimation has capacity of 1.5 MW manufactured by General Electric, China. This turbine is predominantly used in Pakistan [46] and other countries [98–100]. The hub height of the turbine is 80 m and rotor diameter is 80.5 m.
- The number of turbines per square kilometer (turbine density) has been estimated on the basis of spacing between individual turbines. The spacing between turbines is assumed to be 9 rotor diameters in the downwind direction, 5 rotor diameters in the direction perpendicular to the prevailing wind [100]. Eq. (12) is used to estimate the turbine density

$$Dt = 1/((9 \times Rd)(5 \times Rd)) \tag{12}$$

where Dt is turbine density (per square meter) and Rd is rotor diameter (square meters). The estimated turbine density is 3.4 km^2.

- The capacity factor (Cf) for 1.5 MW wind turbine ranges from 30% to 35% [46]. This study assumes 30% CF for potential estimation and the same CF is assumed for the whole planning period (2005–2050).

4.3.4. Methodology

4.3.4.1. The geographical potential. The estimation of wind energy geographical potential is slightly different from the geographical potential estimated for solar and biomass energy sources. It is estimated in terms of suitable area only. This is because of the fact that suitable area is further constrained by application of wind turbines which requires specific distance from one another to have maximum output. Therefore, geographical potential of wind energy is defined as suitable onshore area available for extracting wind power [36]. It can be formulated as under:

$$GPw = Ra \times F \tag{13}$$

where, *GPw* is wind energy geographical potential, *Ra* is resource availability in terms of total available area (km^2) and *F* is suitability factor (%) for wind turbines installation. The total geographical potential is therefore 2481 km^2. This approach of geographical potential estimation is consistent with work of [36].

The geographical potential of wind energy is based on the assessment of wind energy potential in limited sites of Pakistan. Expansion in the selection of sites in future may increase the potential of wind energy in Pakistan. However, whole geographical potential cannot be utilized to extract wind energy due nature of wind turbine technology. Wind turbines are erected at certain distance to extract maximum energy from wind which further limits the area which is geographically available.

4.3.4.2. Technical potential. The technical potential depends upon geographical potential and number of turbines which can be installed in the suitable area and taking into account the capacity factor. Mathematically, it can be written as:

$$TPw = GPw \times Td \times Tc \times 8760 \times Cf \quad (14)$$

where, *TPw* (MW h/year) is technical potential; *GPw* is geographical potential (km^{-2}); Td is turbine density (number of turbines.km^{-2}); Tc is turbine capacity (MW) and *Cf* is capacity factor (%). The technical potential estimated for electricity generation is 34 TW h per year with 12,764 MW of installed capacity.

Wind energy is one of the fastest growing renewable energies for electricity generation in Pakistan in recent years. During 2006–2012, 18 firms (with installed capacity of 50 MW each) have initiated work and are at different stages of completion. Besides, 28 new firms have shown their interest in wind energy generation. It is expected that addition of these new firms will increase the installed capacity of wind based electricity generation up to 3200 MW in the near future [101]. However, this reflects only 25% of available potential in Pakistan. Therefore, more efforts are needed to exploit wind energy for electricity generation in Pakistan.

4.4. Small hydro

4.4.1. Resource description and availability

The term hydro power refers to generation of shaft power from falling water [24]. Like wind energy, hydro power is also an indirect form of solar energy. Water evaporation from the oceans and seas takes place due to solar heating and water then condenses in the form of clouds and falls back to the earth as rain. Hydro power is thus the result of extracting some of this energy when water flows back to the sea [18]. Falling water has kinetic energy which can be converted into mechanical shaft power through a turbine. This power can be used to drive an electric generator. The power available is proportional to the pressure (head) and volume flow rate [102]. Depending on the water flow, hydropower systems can broadly be catagorized into large and small hydro systems. Large scale hydro is based on large dams, where water is allowed to flow in a controled manner [18]. On the other hand, small hydro refers to the extraction of energy from small amount of water flows in rivers, canals and tributaries [102,103]. The difinition of small hydro in different countries is presented in Table 13. In general, small hydro power (SHP) is taken as a power plant having an upper limit of 5 to 50 MW [104], and in Pakistan, the upper limit of SHP is 50 MW [105]. SHPs are built on run-of-river, and therefore do not need extended infrastructure like reservoir or dam to store large amount of water, which leads to considerably less environmental implications [102,103,106].

Pakistan has significant SHP resource especially in hilly areas [107], and the identified potential of small hydro power generation is 2265 MW [105]. This includes its potential on tributaries, run of river and canals. Besides, sites have also been identified for 32 regional dams which are at different planning stages. However, only 14 dams have planned to generate electricity in addition to supplying water for irrigation and drinking. The cumulative capacity of these 14 dams is 46 MW [105]. Moreover, the potential of micro hydro based power generation up to 100 kW on perennial water falls in northern part of Pakistan is estimated to be 300 MW [108]. Total identified potential is therefore 2958 MW. Detail of the potential is given in Table 14.

Table 13
Small hydro definition in different countries/regions of the world [109].

Country/region	Limit (MW)
Canada and China	≤ 50
Brazil	≤ 30
India	≤ 25
European Union	≤ 20
Sweden	≤ 15
Norway	≤ 10
United States	5–100

Table 14
Detail of identified potential of small hydro in 2011 [105,108].

Site description	Potential (MW)
Tributaries	1591
Canals	674
Dams	46
Micro hydro	300
Run-of river	347

4.4.2. Overview of technologies

Extraction of energy for electricity generation depends upon flow rate and resulting varying water pressure and speed conditions. Therefore, the technologies (turbines) for electricity generation can broadly be divided into two subcategories. These are impulse turbine and reaction turbine [18,90]. Impulse turbines are Pelton and cross-flow turbines, while reaction turbines are Francis, Propeller, Kaplan and Straflo turbines [90]. Reaction turbines run faster and have higher efficiencies and therefore more commonly used for power generation from small hydro power plants [109].

4.4.3. Assumptions

The assumptions used for estimation of small hydro potential are:

- Only grid connected power projects below 50 MW are considered for the estimation of small hydro potential. Micro hydro and other smaller power projects (installed capacity below 100 kW) are excluded.
- Existing and future power plants have been included.
- The estimation of energy generation from various projects have been taken from available literature [110,111]. Details of existing and some future power projects is given in Table A-4 (Appendix-A).
- The average per Megawatt electricity generation is 4.25 GW h (Table A-4 (Appendix-A)). This value is used to estimate the expected energy generation for the remaining potential.
- The conversion efficiency is assumed to be 80% [105].

4.4.4. Methodology

4.4.4.1. Geographical potential. The geographical potential of small hydro is estimated in terms of installation capacity suitable for grid connected small hydro rather than suitable area. The geographical potential of small hydro is:

$$GPsh = Ra \times F \tag{15}$$

where, *GPsh* (MW) is geographical potential of small hydro; *Ra* is resource availability in terms of total available potential (MW) (Table 10) and *F* is the potential suitable for grid connected electricity generation (%). The potential which is not suitable for grid connected micro hydro projects accounts for 10.14% of the total potential. Therefore the geographical potential is estimated to be 2658 MW.

The geographical potential of small hydro is based on the identified sites till 2011. Further improvement in technology may increase the potential in future. However, in Pakistan water availability on these sites is seasonal which restricts electricity generation.

4.4.4.2. Technical potential. The technical potential of electricity generation depends on geographical potential and conversion efficiency. As the source is site specific and data is not fully available to estimate conversion efficiency for each site, the per unit (MW) electricity generation is used to estimate the total technical potential. From available data, average per unit electricity generation is 4.25 GW h (Table A-4 (Appendix-A)) and so the technical potential of small hydro is 11 TW h per year.

Small hydro power sector remained stagnant for the last 60 years (1950s–2010). The total installed capacity in 1960s was 108 MW which increased to 287 MW in 2010 (Table A-5 (Appendix-A)). However, small hydro based power generation has recently been focused by the government mainly with help of Asian Development Bank (ADB), and in 2006 work has started on many run-of-river and canal based projects with a cumulative capacity of 84 MW [111]. With expected addition of more projects, the cumulative capacity of small hydro electricity generation will be in 312 MW in 2019 [105]. However, it is still 12% of total available potential. More concrete efforts and policy decisions are therefore required to make this option viable.

5. Results and discussion

The 2010–2050 geographical and technical potential of selected renewable energy sources estimated for Pakistan is given in Table 15.

The renewable energy potential (167.7 GW) has 8 times more potential than the total electricity demand in the country (21 GW) in 2010. In 2005, the government planned the target of having 10% of the total installed capacity in the country from RES by 2012 [23]. However, no grid connected renewable based installed capacity was added during 2005–2008. In 2008, the government revised the target of increasing share of renewable energy and set 5% of total installed capacity from renewables till 2030 [4]. The details of the plan are given in Table 16.

Table 15
Estimated electricity capacity from renewable energy sources 2010–2050 (GW).

	2010	2020	2030	2040	2050
Wind (grid connected)	12.8	12.8	12.8	12.8	12.8
Solar PV (DCNT)	9.9	14.1	19.1	24.5	29.9
Solar PV (CNT)	116.2	116.2	116.2	116.2	116.2
Solar thermal (CNT)	22.6	22.6	22.6	22.6	22.6
Biomass (field residues)	1.7	2.0	2.5	3.0	3.7
Biomass (animal waste)	1.6	2.3	2.8	3.4	4.1
Biomass (MSW)	0.2	0.4	0.7	1.1	1.9
Small Hydro	2.7	2.7	2.7	2.7	2.7
Total	167.7	173.0	179.3	186.1	193.9

Table 16
Plan for promotion of renewable energy in the power sector of Pakistan (MW) [115].

Source	2010	2015	2020	2025	2030
Wind	100	800	2000	3500	6000
Solar	1	100	500	1000	1500
Biomass	60	300	500	750	1000
Small hydro	1	150	500	800	12000
Total	162	1350	3500	6050	9700

Table 17
The total available potential and expected installed potential till 2015 (MW).

Energy Source	Technology	Total potential (2010)	Capacity addition	Total installed capacity	Remaining potential
Wind	CNT	12,764	900	900	11,864
Solar PV	DECNT	9,893	0	0	9,893
	CNT	116,197	1	1	116,196
Solar thermal	CNT	22,587	0	0	22,587
Biomass	CNT	5,420	24	24	5,396
Small hydro	CNT	2,658	166	312	2346
Total		169,519	1091	1237	168282

To materialize this plan, a number of incentives (financial and fiscal) are offered for investors in addition to surety of purchasing all the electricity generated. Fiscal incentives include tax exemption on income and machinery and equipment. Major financial incentive is permission for power generation companies to issue corporate registered bonds and shares.

Future prospects of renewable energy in Pakistan, however, are encouraging, especially in case of wind energy. Table 17 gives details of renewable based power plants to be commissioned till 2015.

Table 17 shows that the planned installed capacity is still lower than the target except for wind energy, where the planned capacity is ahead of target by 100 MW. In case of small hydro, progress has been made. However, there is a lack in the promotion of solar based electricity generation projects despite its enormous potential, though in a number of developing countries solar energy is used for power generation. China has 3093 MW installed capacity of grid connected solar PV in 2011. Thailand is implementing 149 MW solar PV plants till 2011 [112,113]. Similarly, solar thermal power plants are being planned in China, India, Turkey and Thailand. Construction of MSW based power plants can help in reducing the electricity crises in Pakistan and also improve the local environment by reducing solid waste. India has already installed 372 MW of MSW based power plants [114]. Thailand has MSW based power generation since 2009 [115]. Therefore, there is an urgent need of concrete policy actions for promotion of renewable energy in the power generation sector.

6. Conclusion

The electricity demand in Pakistan is increasing with increasing population, expansion of industrial networks and improvement in lifestyles. Production of electricity is currently heavily dependent on fossil fuels. Limited domestic availability and increasing prices of fossil fuels are resulting in lower supply of electricity, and the demand - supply gap is increasing. Under such

Table A-1
Comparison of main characteristics of the CSP technologies.
(*Source*: [33].)

Characteristics	Parabolic trough	Solar tower	Tower linear	Dish-sterling
Maturity of technology	Commercially proven	Pilot commercial projects	Pilot projects	Demonstration projects
Key technology providers	Abengoa solar, solar millennium, sener group, acciona, siemens, nextEra, ACS, SAMCA, etc	Abengoa solar, brightSource, energy, eSolar, solar reserve, torresol	Novatec solar, areva	
Technology development risk	Low	Medium	Medium	Medium
Operating temperature (°C)	350–550	250–565	390	550–750
Plant peak efficiency (%)	14–20	23–35	18	30
Annual solar-to-electricity efficiency (net) (%)	11–16	7–20	13	12–25
Annual capacity factor (%)	25–43	55	22–24	25–28
Grid stability	Medium to high	High	Medium	Low
Cycle	Superheated rankine steam cycle	Superheated rankine steam cycle	Saturated rankine steam cycle	Stirling
Steam conditions (°C/bar)	380 to 540/100	540/100 to 160	260/50	n.a
Water requirement (m^3/MW h)	3 (wet cooling) 0.3 (dry cooling)	2–3(wet cooling) 0.25(dry cooling)	3 (wet cooling) 0.2 (dry cooling)	0.05–0.1 (mirror washing)
Application type	On-grid	On-grid	On-grid	On-grid
Suitability for air cooling	Low to good	Good	Low	Best
Storage with molten salt	Commercially available	Commercially available	Possible, but not proven	Possible, but not proven

Table A-2
Detail of biomass power generation technologies.
(*Source*: [116].)

Characteristic	Steam turbine	Gas/ combustion turbine	Micro-turbine	Reciprocating IC engine	Fuel cell	Sterling engine
Size	50 kW to 250 MW	500 kW to 40 MW	30 kW to 250 kW	Smaller than 5 MW	Smaller than 1 MW	Smaller than 200 kW
Fuels	Biomass/Biogas	Biogas	Biogas	Biogas	Biogas	Biomass/Biogas
Electric efficiency	5 to 30%	22 to 36%	22 to 30%	22 to 45%	30 to 63%	5 to 45%
Field experience	Extensive	Extensive	Extensive	Extensive	Some	Limited
Commercialization status	Many models available	Many models available	Limited models available	Many models available	Commercial introduction and demonstration	Commercial introduction and demonstration
Installed cost (as CHP system)	$350 to $750/kW (without boiler)	~ $700 to $2,000/kW	$1,100 to $2,000/kW	$800 to $1,500/ kW	$3,000 to $5,000/kW	Variable $1,000 to $10,000/kW
Operations and maintenance (O and M) costs	Less than 0.4 ¢/kW h	0.6 to 1.1 ¢/kW h	0.8 to 2.0 ¢/kW h	0.8 to 2.5 ¢/kW h	1 to 4 ¢/kW h	Around 1 ¢/kW h

Table A-3
Composition of MSW in different cities of Pakistan (%).
(*Source*: [50].)

	GWA[a]	FSD[a]	KRI[a]	HYD[a]	PWR[a]	QTA[a]	IBD[a]	MTN[a]	LHR[a]	AVG[a]
Plastic and rubber	5.00	4.80	3.60	3.20	3.70	8.60	2.82	4.48	5.63	4.65
Metals	0.30	0.20	0.75	0.50	0.30	1.20	0.05	0.30	0.32	0.44
Paper	2.50	2.10	2.40	3.40	2.10	1.20	0.67	2.40	2.70	2.16
Cardboard	1.80	1.60	1.50	1.50	1.90	1.30	0.37	–	0.00	1.25
Rags	3.20	5.20	4.70	4.30	4.30	5.10	2.12	6.98	7.45	4.82
Glass	1.50	1.30	1.60	3.40	1.30	1.50	0.38	0.80	0.70	1.39
Bones	3.20	2.90	2.00	2.00	1.70	2.00	0.38	1.03	0.86	1.79
Food waste	14.70	17.20	20.00	22.00	13.80	14.30	66.53	32.35	30.50	25.71
Animal waste	1.00	0.80	5.80	6.00	7.50	1.70	0.00	2.65	2.53	3.11
Leaves, grass etc.	12.80	15.60	13.50	13.50	13.50	10.20	25.54	20.21	20.20	16.12
Woods	0.80	0.70	2.25	2.25	0.60	1.50	0.08	1.30	1.24	1.19
Fines	47.50	43.00	38.90	34.40	42.00	43.60	0.12	27.50	0.00	30.78
Stones	5.70	4.60	3.00	3.20	7.30	7.80	0.94	–	27.65	7.52
Share (%)										
Organic	40	46	52	55	45	37	96	67	65	56
inorganic	60	54	48	45	55	63	4	33	34	44

[a] GWA=Gujranwala; FSD=Faisalabad; KRI=Karachi; HYD=Hyderabad; PWR=Peshawar; QTA=Quetta; IBD=Islamabad; MTN=Multan; LHR=Lahore; AVG=Average.

Table A-4
Detail of capacity and energy generation from committed small hydro plants in Pakistan.
(*Source*: NTDC [3,110,111])

Project name	Capacity (MW)	Generation (GW h)	Unit generation (GW h/MW)
Khokhra	3.20	13.97	4.37
Marala	7.20	28.39	3.94
Chianwali	5.00	23.58	4.72
Degout fall	5.00	21.84	4.37
Okara	4.00	17.47	4.37
Pakpattan	3.20	14.41	4.50
Basho	28.00	122.56	4.38
Harpo	33.00	144.45	4.38
Pehur	18.00	57.70	3.21
Average			4.25

Table A-5
Current status of small hydro power projects 2011 (MW) in Pakistan.
(*Source*: PPIB [105,107])

	Total	In operation	Under implementation
Tributaries and ROR	1938	242	647
Canals	674	45	133
Small dams	46		46
Total	2658	287	826

circumstances it is imperative for the country to look for alternative domestic resources. The long term geographical and technical potential of renewable energy sources has been estimated and presented. In 2010, the country had 168 GW installed capacity potential which is 8 times more than total electricity demand, of which renewable based installed capacity was less than 1% of total installed capacity. Though the government has planned to increase the share of renewable based capacity to 5% of the total installed capacity (9.7 GW) till 2030, even this capacity is far less than the available potential (179 GW) in 2030. The technical potential of solar, biomass, wind and small hydropower for 2010 is estimated to be 148.7, 3.6, 12.8 and 2.7 GW, respectively, and the corresponding values for 2050 are 168.7, 9.8, 12.8 and 2.7, respectively. The technical potential of only wind based power is exploited at a significant level. Exploitation of solar and biomass resources can help the country in developing a sustainable energy base and at the same time enhance energy security of the country by reducing its dependence on imported fossil fuels.

Appendix-A

See Tables A1–A5 below.

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